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Flux jumps in Nb_3Sn magnets

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Abstract

This note describes a model of heat generation in Nb_3Sn strands due to the flux jumps that may be related to the premature quenching of the Fermilab shell and racetrack dipole magnets.

Energy balance in Nb_3Sn strand

Magnetization of Nb_3Sn OST strands used in the high field dipole models was measured at Fermilab short sample test facility [1]. Figure 1 presents typical strand magnetization in 0-3 T field cycle, related to the total strand volume.

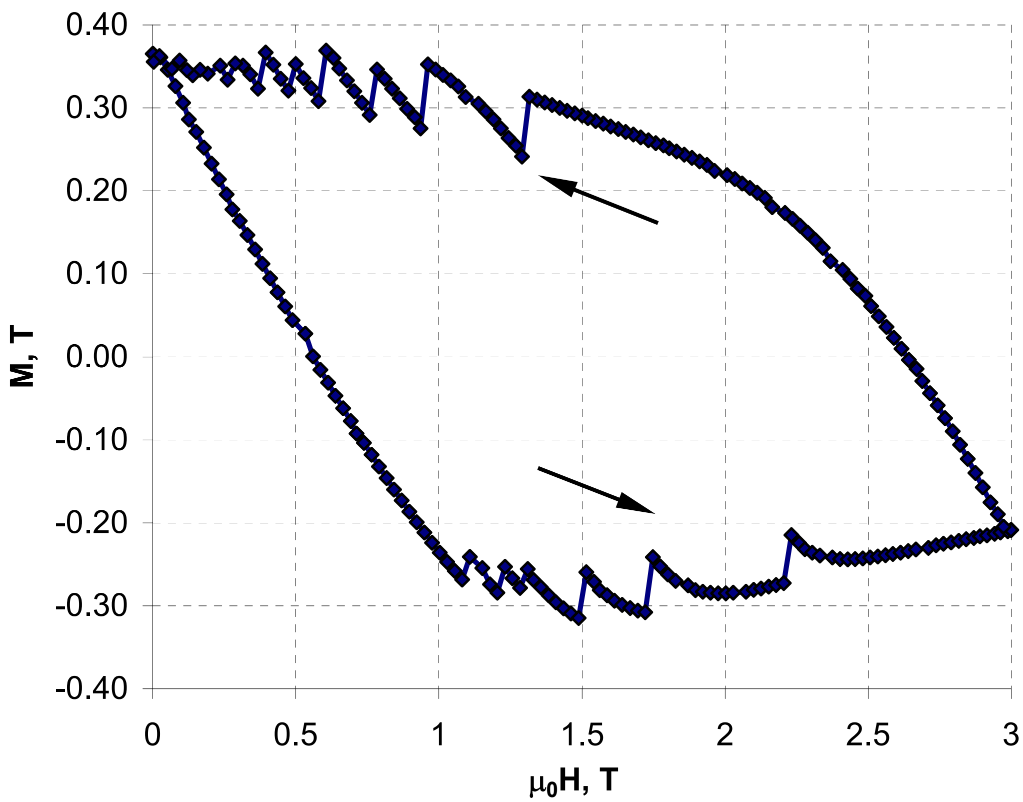

Figure 1. Nb_3Sn strand magnetization.

Any field change in a magnetic media corresponds to variations of energy stored in the magnetic field. Energy density in any point of space is described by

$$\omega = \frac{\vec{B} \cdot \vec{H}}{2}.$$

At the same time, the flux density in a magnetic media is bound to its magnetization by the following expression

$$\vec{B} = \mu_0 \vec{H} + \vec{M}.$$

Then

$$\omega = \frac{(\mu_0 \vec{H} + \vec{M}) \cdot \vec{H}}{2},$$

which for isotropic magnetic media (that is the case for superconductor) transforms into

$$\omega = \frac{\mu_0 H^2 + MH}{2}.$$

The latter allows deriving the energy density from the measured magnetization curve, as shown in Figure 2.

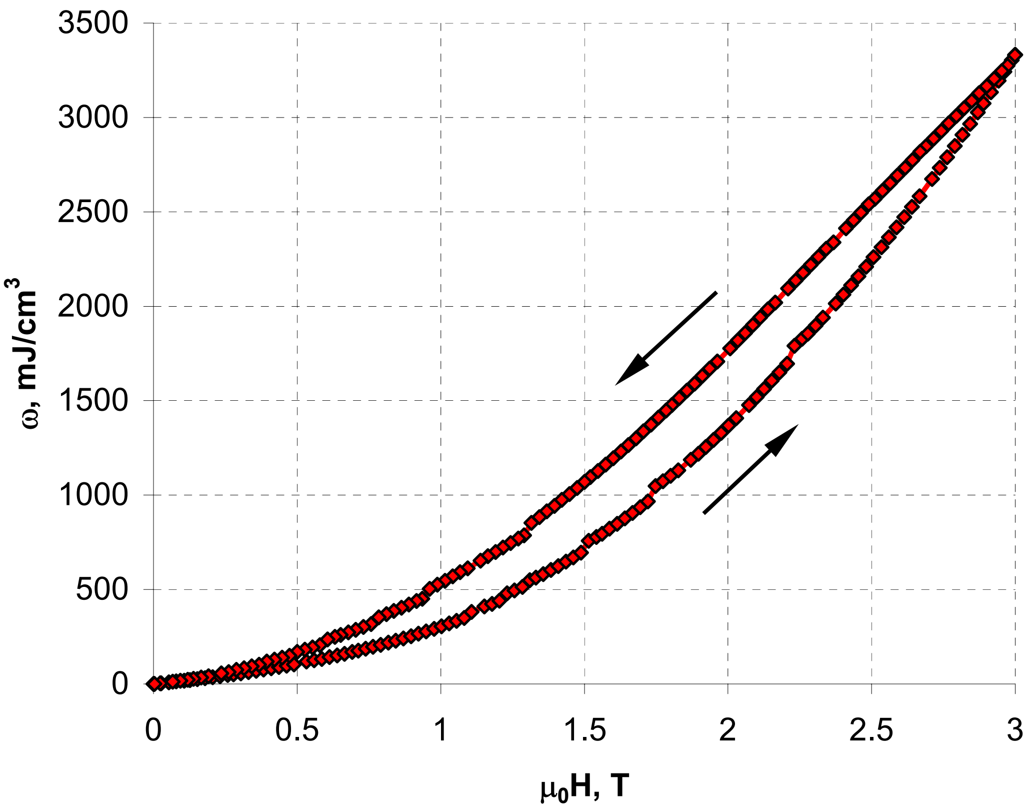

Figure 2. Energy density as a function of applied field.

Most of the energy stored in the magnetic field during the field ramp up returns to the power supply. It can be found as the energy stored in non-magnetic media (vacuum), exposed to the given field

$$\omega_0 = \frac{B \cdot H}{2} = \frac{\mu_0 H^2}{2}.$$

Then, subtracting ω_0 from ω one finds that relatively small fraction of total energy, dissipating inside the superconductor in form of heat that is usually referred to as hysteretic losses

$$\omega_l = \frac{MH}{2}.$$

Figure 3 presents density of hysteretic losses as a function of applied field. Note that normally the energy dissipation occurs in relatively long cycle, when the heat is safely removed by the cryogenic system. However, it is not the case for the energy jumps (corresponding to the flux jumps in the superconductor), which instantaneously (in a range of milliseconds) release relatively large amounts of heat. For the considered OST strand, the energy jumps heating the conductor in adiabatic mode are in the order of 40-50 mJ/cm^3.

Having found the energy dissipations and before moving on to the thermal analysis a simple "reality check" is advisable.

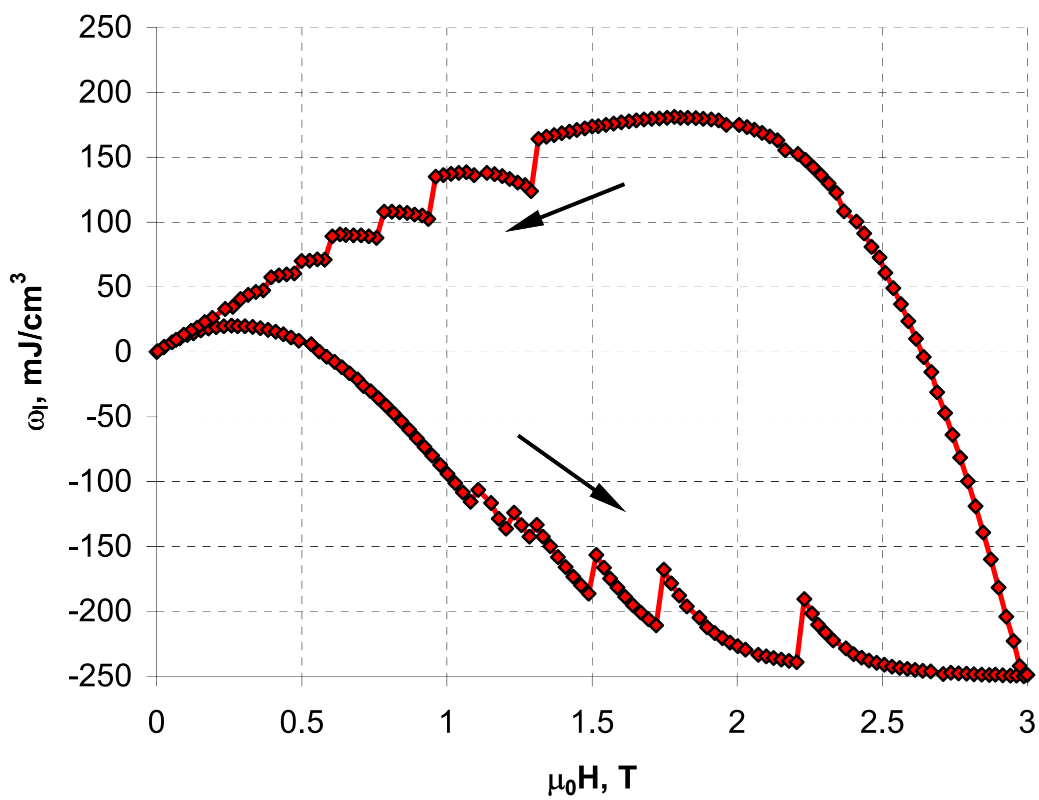

Figure 3. Energy balance in Nb_3Sn.

The reality check

In order to make sure that the energy calculations are reliable, and that the strand magnetization measured on a short sample represents the coil magnetization, one may compare the calculated energy dissipations per cycle with what was measured on the magnet models. The energy dissipated in cycle per a unit of volume is

$$\Delta\omega_l = \frac{1}{2}\oint M(H)dH \ .$$

For the magnetization curve presented in Figure 1, the energy integral gives 447 mJ/cm^3. Multiplying it by the coil area of 22.33 cm^2 and the model magnetic length of 81 cm one obtains 808 J of energy dissipated per cycle. This number matches well with the values of 850-900 J measured in HFDA03-04 magnets [2], which are slightly larger due to addition of hysteretic losses in the iron yoke.

Thermal analysis

Taking into account fast nature of the flux jumps, the thermal calculations were done in adiabatic mode without heat transfer from the strand to surrounding media. In order to determine strand temperature after an instantaneous heat release, the specific heat functions shown in Figure 4 were used [3]. For easier analysis they were transformed into volumetric functions, shown in Figure 5 using density of 8.9 g/cm^3 for copper and 3.6 g/cm^3 for Nb_3Sn.

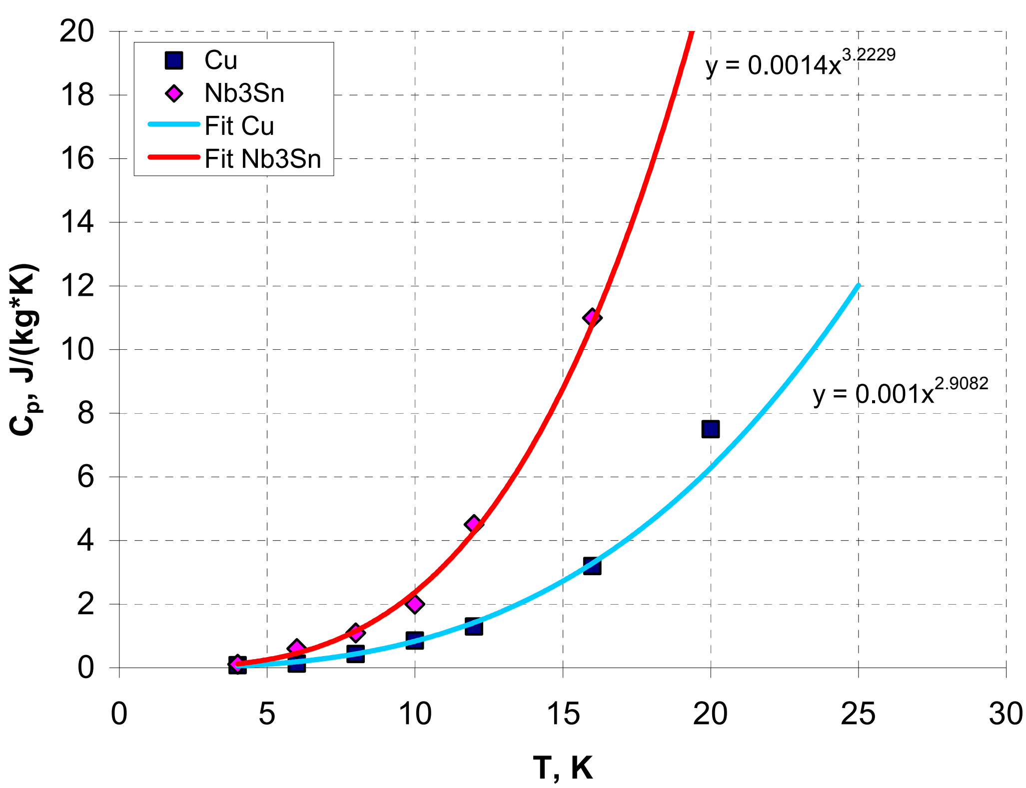

Figure 4. Specific heat of Cu and Nb_3Sn.

The amount of energy necessary to heat the strand from the temperature T_0 to T at adiabatic conditions can be determined as

$$Q(T) = \int_{T_0}^{T} C_p(T)dT ,$$

which for the Nb_3Sn composite fit given in Figure 6 leads to

$$Q(T) = 0.001615 \cdot T^{4.0864} \Big|_{T_0}^{T} ,$$

where T is in [K] and Q(T) is in [mJ/cm^3].

Figure 6 presents the heating energy as a function of temperature, calculated for the initial temperature T_0=4.5 K. The plot demonstrates that instantaneous energy dissipation of 50 mJ/cm^3 due to a single flux jump leads to the strand heating up to 12.6 K.

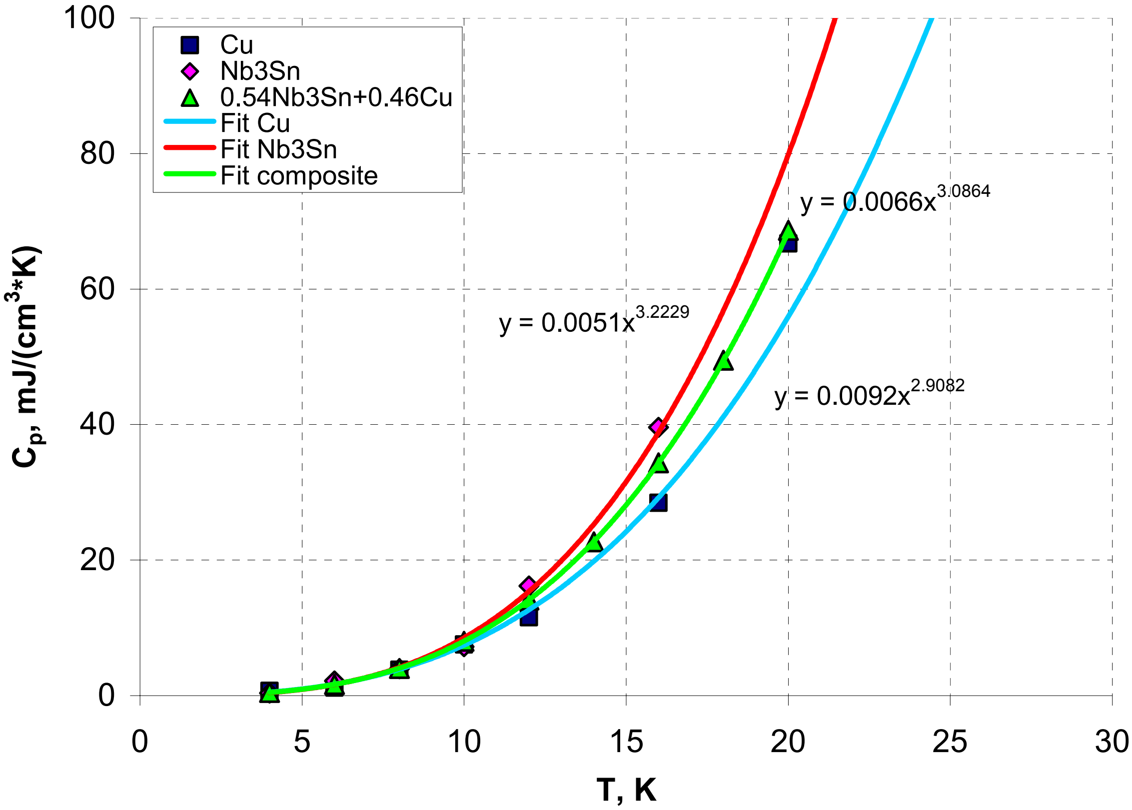

Figure 5. Specific heat of Cu, Nb_3Sn and composite with the Cu/non-Cu ratio of 0.85.

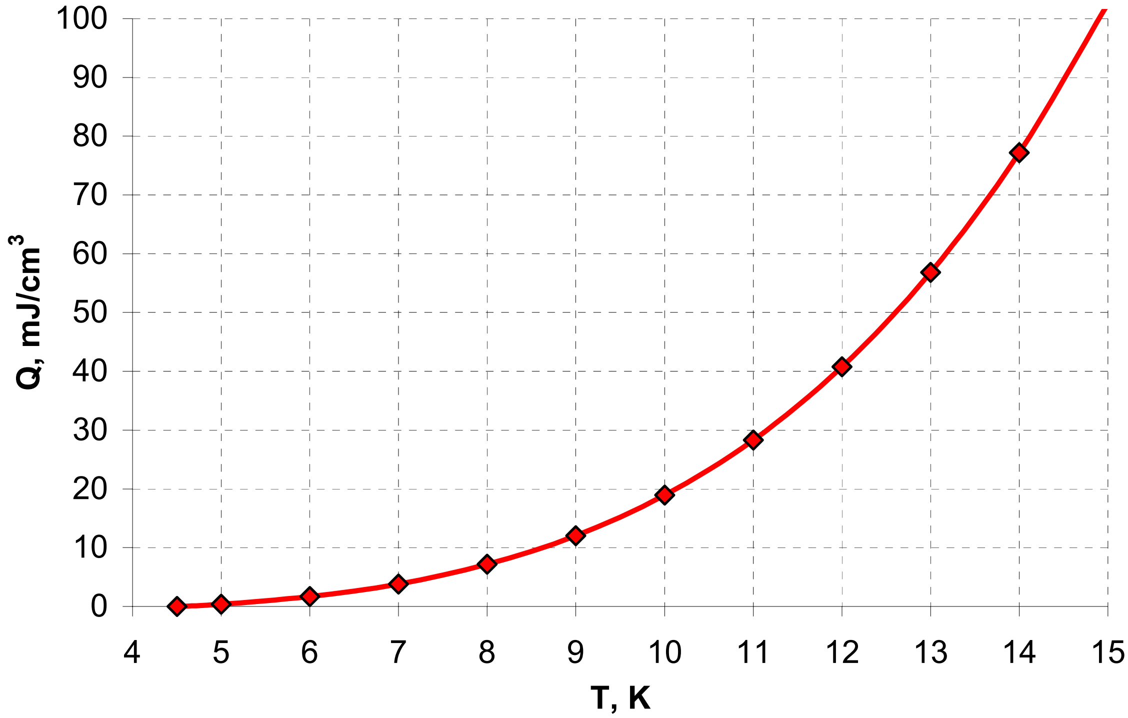

Figure 6. Heating of Nb_3Sn strand.

Impact on the magnet performance

There are two types of FNAL Nb_3Sn magnets built up to now showing the premature quenching – the shell and racetrack dipoles. Figure 7 shows the field distribution inside the coils at the average measured quench currents of 8 kA and 12 kA respectively for the shell and racetrack magnets. Figure 8 presents critical temperatures as functions of field in those magnets at the quench currents. The short sample limits (after the relevant degradation taken into account) were assumed 1600 A/mm2 and 1400 A/mm2 at 12 T and 4.2 K respectively for the shell and racetrack magnets.

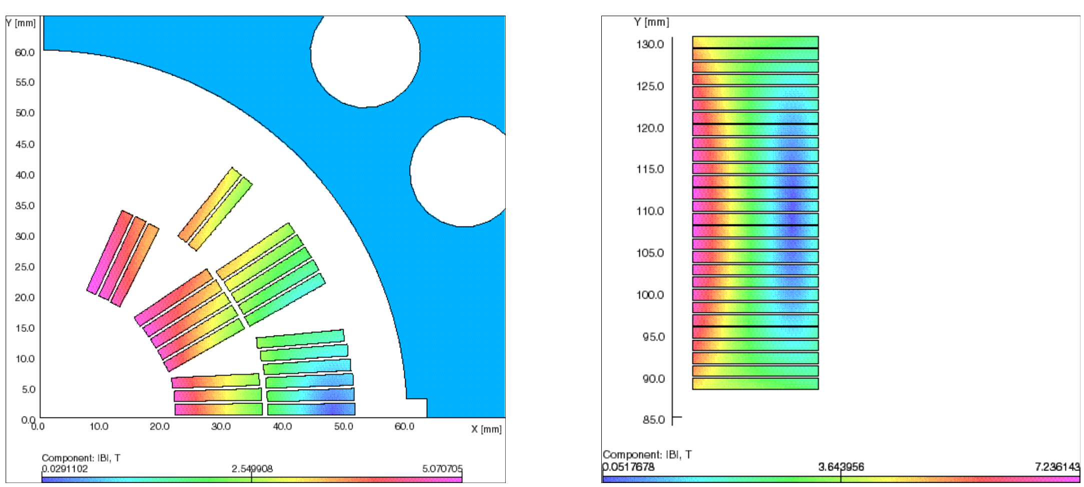

Figure 7. Field distribution in the shell and racetrack coils at quench.

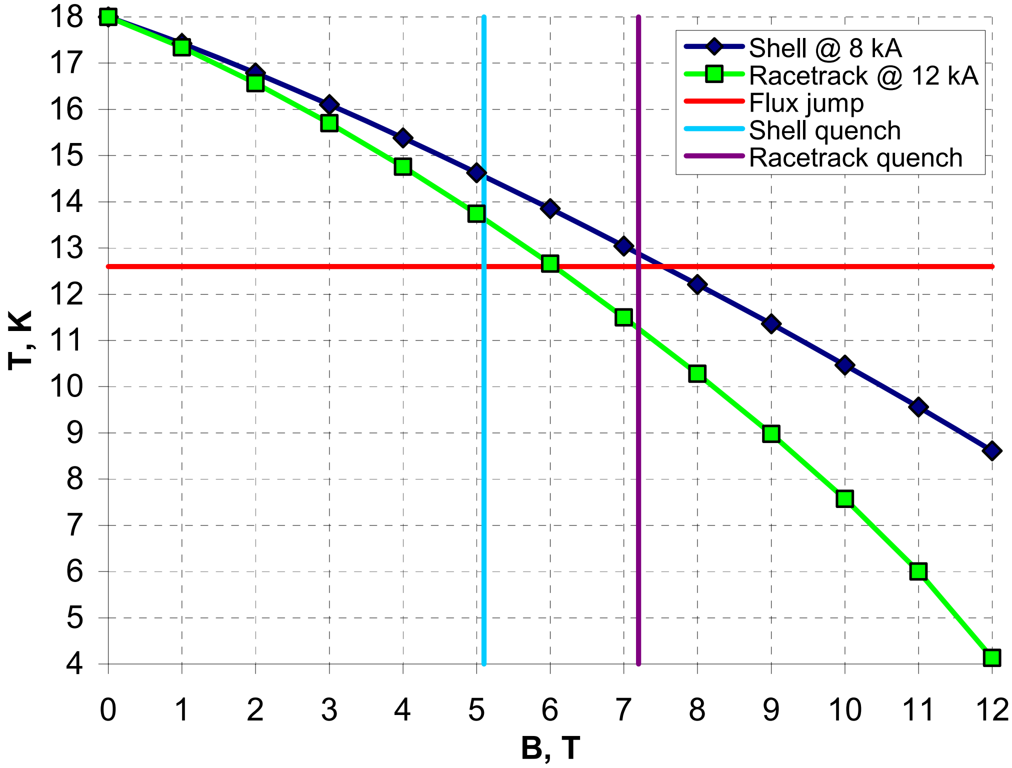

Figure 8. Critical temperatures of the shell and racetrack magnets.

It is easy to see that a single energy jump of 50 mJ/cm^3 alone cannot cause quench in the shell type magnet at the given current even if it happens in the whole coil volume (of course assuming the coil was at 4.5 K before the jump).

The situation with racetrack is more complicated. The point corresponding to the temperature generated by a flux jump and field in the magnet at given current lies above the critical surface, which means the magnet would necessarily quench from a single flux jump occurred the whole coil volume.

According to Figure 1, the flux jumps happen only in the low-field region, between 1 T and 2.5 T during the ramp up. Due to the transposition, strands go from the low to high field region on a relatively short length (half twist pitch). Therefore, the heat generated due to the flux jump in the low field region may bring part of the strands exposed to the high field above the critical surface. From Figure 7 follows that approximately half of the racetrack coil is in the field region where the flux jumps occur. If the flux jump takes place in 50% of the coil, but the heat is distributed in the whole coil volume – the coil temperature would be 10.5 K that is just 0.7 K below the critical temperature.

Conclusion

The heat generation in Nb_3Sn strands due to the flux jumps was analyzed based on experimental data. The analysis shown that the jumps correspond to relatively large amounts of energy being released within short periods of time, which heat the strands up to 12.6 K.

Such temperature rise alone could not cause quenches in the shell type magnets at 8 kA, but in combination with mechanical damage or extra heating might bring the superconductor above the critical surface.

The premature quenching in the racetrack magnet can very well be explained under assumption of the flux jumps in ~50% of the coil volume exposed to low field and following heat propagation to the high field region. If this is the case, the next racetrack magnet will show no essential improvement of the quench performance.

In order to draw more definite conclusions, a detailed study of the strand instabilities is required. The presently available data do not address questions about reproducibility of the flux jumps in different strand samples, scaling of the jump field with temperature (i.e. if the local temperature rise from a flux jump can initiate the flux jumps in other parts of the strand), volume of the flux jump as function of the field gradient along the strand, etc.

As general solutions to the strand heating problem, reduction of the flux jump amplitude or field gradient across the coil are necessary. When the latter requires essential changes in magnet designs, it was demonstrated that using of non-standard heat treatment cycles may eliminate the flux jumps in Nb_3Sn, even though the strand magnetization remains high [1].

References

1. E. Barzi, P.J. Limon, R. Yamada, A. Zlobin, Study of Nb_3Sn Strands for Fermilab's High Field Dipole Models, IEEE Transactions on Applied Superconductivity, Vol. 11, No. 1, March 2001, pp.3595-3598.
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